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Influence of some interstitial materials on the thermal contact conductance

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INFLUENCE OF SOME INTERSTITIAL MATERIALS ON THE THERMAL CONTACT CONDUCTANCE

BY

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ABSTRACT

Experiments have been conducted to investigate the effect of the interstitial materials at the interface of metals in contact. The test specimens were cylinders, axially aligned and loaded. Specimen materials were 6061-T6 aluminum alloy, and the contact fillers were stainless steel wire screens, aluminum foil, paper, and dielectric greases. The tests were conducted at atmospheric environment. The contact pressure ranged from 25 psi to 600 psi. The mean interface temperature ranged from 100 ^{o}F to 200 ^{o}F. Surface roughnesses of specimens were from 25 to 35 micro-inches, rms.

The results of the investigation reveal that if the contact surfaces are sandwiched with interstitial material, the interface conductance is primarily dependent upon the thermal conductivity of this interstitial material. Some materials such as wire screen have the advantage of being less dependent upon temperature, pressure, and contact surface conditions, compared to bare junctions. The interstitial materials can either increase or decrease the contact resistance. In the case of aluminum foil sandwiched between the aluminum surfaces, the interface conductance increases three times, and sandwiched with greases, increases 10 times as much as that of the aluminum bare junction. On the other hand, if sandwiched with paper the interface conductance is lowered to 70 percent.

This paper presents various characteristics of interstitial materials and provides some reliable data for engineering design purposes and further analysis in this field.

ACKNOWLEDGEMENTS

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I. INTRODUCTION

When two metals at different temperatures are brought into contact, energy is transferred across the interface of contact. If two plane metal surfaces could be obtained free of oxide contamination and brought into perfect contact without any air included between them, the interfacial resistance would be negligible. However, this condition is an optimum one not obtainable in practice.

All metal surfaces, even when highly polished or flat, show appreciable contact resistance to heat flow. This resistance is caused by a lack of complete contact between the joined surfaces; i.e. when two surfaces are pressed together, contact is actually made only at a few discrete points. At atmospheric conditions, heat flow across the interface contact consists of three methods :

(1) heat conducted through the actual contact area points
(2) through the air filling the spaces between the contacts, via conduction and convection
(3) radiation across the voids or interstitial gas

The measurement and prediction of thermal contact conductance has received considerable attention. However, only a very limited amount of data for the contact conductance of metallic joints with interstitial fillers are tabulated for ready use. Generally only trends are shown, and there is very little correlation.

The use of contact filler materials has the advantage of less sensitivity to loads and surface conditions. The insertion of interstitial materials can serve to increase or decrease the thermal resistance of the junction.

The objective of this investigation is to increase the understanding, based on experiment, of contact resistance with the existence of interstitial materials, and to establish some reliable data for general design purposes and further analysis in this field.

II. REVIEW OF LITERATURE

When two metal surfaces are brought together to form an interface, the solid-to-solid contact area between them is generally a small fraction of the apparent area over which they meet. This direct contact area may be less than 1 percent of the total and rarely exceeds 10 percent unless bonding agents are introduced. Boeschoten and Van Der Held(1) found that the area of metal in actual contact was in the order of 1% of the total area of contact at a pressure of 500 psi. When the pressure on the contact is increased the peaks in contact will be deformed and the contact points will increase both in size and in number. As observed by A. J. W. Moore(2), when two metal surfaces are pressed together, the irregularities of the softer surface undergo full plastic deformation while the peaks of the harder metal are embedded in the other surface.

In the case of heat transfer through materials, the interface gives rise to an additional thermal resistance since the contact between surfaces is never perfect. As shown in Figure 1, the net effect of the interface on the transport process is the formation of a temperature discontinuity. This discontinuity results from the imperfect nature of the contact as drawn schematically in Figure 2. As the interface is approached, the flux lines tend to converge to the direct solid-to-solid contact points since for metallic contacts this flow path offers considerably less resistance than the void areas around the contacts which are generally filled with air or, are evacuated. On the avarage, the isotherm 1 is at a higher

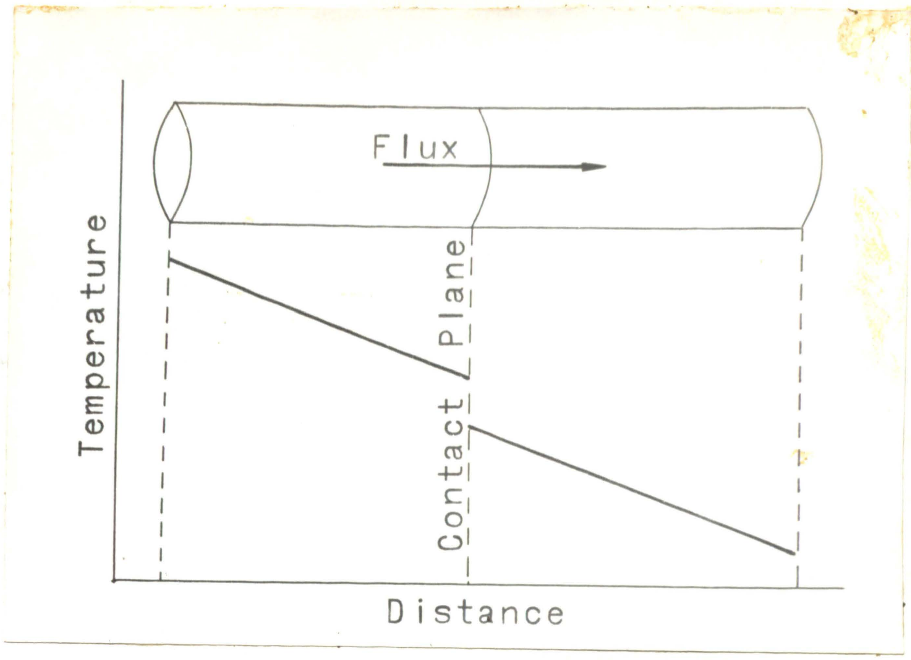

Figure 1. Interfacial Resistance Reflected as Temperature Discontinuity

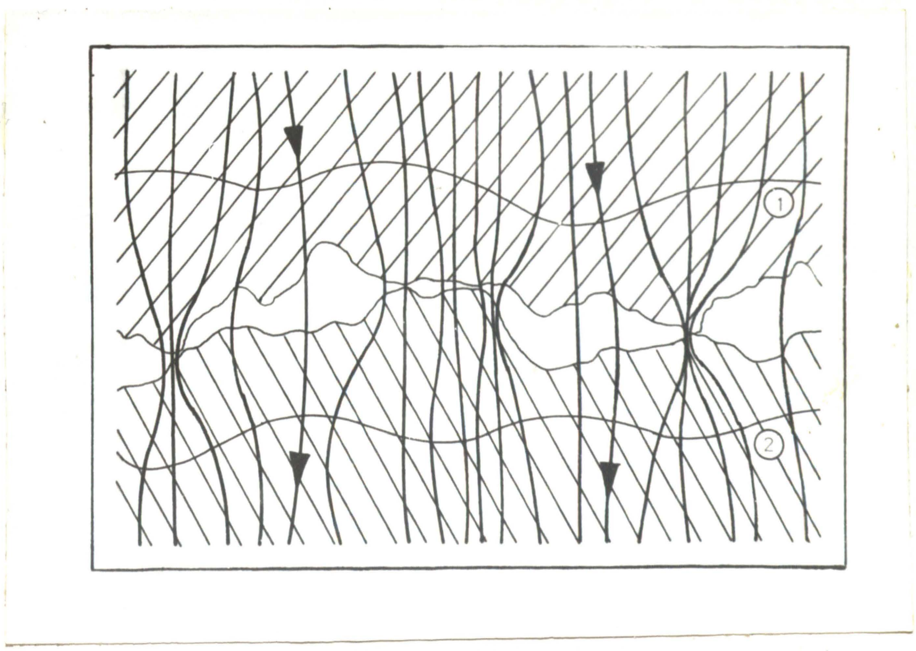

Figure 2. Flux Field Distribution at an Interface

temperature than it would be in the absence of an interface and the isotherm 2 is at a lower average temperature. The result is the formation of a temperature discontinuity at the interface as shown in Figure 1.

The thermal resistance at an interface is not a simple property of the materials but is dependent upon a number of factors. These include (i) the contact pressure, (ii) the manufacture conditions - flatness, roughness, (iii) the existence of interstitial materials, fluids, (iv) surface conditions - contamination, oxidation, and (v) the junction temperature. Each of these factors are briefly discussed below :

(i) The Contact Pressure : Barzelay, Tong and Holloway(3) conducted one of the earlier experimantal works to determine the factors influencing the thermal conductance across the interface. They found the mechanical pressure applied to an interface has a major influence on the resulting thermal contact conductance. The effect was large in the low pressure range (between 0 and approximately 100 psi), but leveled off in the higher pressure range. The same trends are also shown in the work carried out by Stubstad(4), Smuda, Fletcher, Gyorog(5) and many others. Barzelay, et. al., also concluded that for a given pressure increment and interface temperature the absolute increase of conductance is higher for smoother surfaces.

(ii) The Manufacture Conditions - Flatness, Roughness : Experimental results presented by Bloom(6) and Fried(7) showed that thermal contact conductance increases as surface roughness and flatness deviation decrease. In the work of Clausing and Chao[8], however, results of several tests showed that contact conductance increases with increased surface roughness and flatness deviation, while results of the remainder of their tests exhibit the opposite trend. Thus more comparative tests must be run since such a wide variation of thermal contact conductance with surface finish exists.

(iii) The Existence of Interstitial Materials, Fluids : The existence of interstitial materials or fluids can either increase or decrease the contact resistance. Koh and John[9] noted that the smaller the Brinell hardness of the interstitial material, the greater the increase in contact conductance. In their work, copper, aluminum, lead and indium foil were used as comparative interstitial materials. Fried and Costello[10] showed the interstitial materials with Meyer hardnesses (the average resistance to indentation) lower than the structural materials can improve the interface conductance considerably. On the other hand, the interstitial materials introduced by Smuda and Gyorog[11] showed an entirely different effect. These materials with their low thermal conductivities decreased the contact conductances to a lower wide range. Summarizing these investigations, the contact conductance is dependent more upon the mechanical and thermal properties of interstitial materials than upon the contact surface finish conditions, i.e. flatness, roughness. This is not true for the contact conductance of bare metal junctions. In this case, the contact conductance is primarily dependent upon the surface finish conditions. Held[12] made an analytical study and obtained some experimental data to check out the theoretical work. He observed that the conductance due to air in the gaps was remarkably high, representing an overwhelming proportion of the total conductance. In his experiment, his surfaces were very rough and the apparent pressures were quite low.

Only a very limited amount of data for the contact conductance of metallic joints with interstitial fillers is tabulated, and generally only trends are shown. Values presented are rarely defined in a similar manner, and test conditions are not uniform. Thus there has been very little correlation of results.

(iv) Surface Conditions - Contamination, Oxidation : Surface contamination and oxidation may be present in the form of a thin film over the metal surface. It is very difficult to define the degree of contamination and oxidation. Since films vary widely in their properties and thickness, their resistance to the flow of heat also varies considerably. The insulating effect of surface films is known to cause servere disturbances in electrical contacts; however, their contribution to thermal contact resistance is not clear. Because of insufficient knowledge of the formation and growth of films, it is not possible at this stage to draw any definite conclusions.

(v) The Junction Temperature : Rogers[13] reported that in a vacuum environment the thermal contact conductance increased only slightly with increasing mean temperature. Clausing and Chao[8], on the other hand, showed that at a constant load the interface conductance increased appreciably and rather uniformly with the interface mean temperature. It is thus seen that the junction temperature is a factor of indefinite effect. Hence in this investigation, several interface temperatures were established at each load to study the effect of junction temperature.

In the course of these investigations, many interesting phenomena were noted.

Barzelay, Tong and Holloway[(3)] noted that when steel and aluminum were in contact, the interface conductance depended upon the direction of heat flow. The conduction from aluminum to steel was appreciably larger than that from steel to aluminum. Their tests were performed in air at atmospheric pressure. When the direction of heat flow was reversed, the specimens were also rearranged and, hence, the contact configuration was changed.

Rogers[(13)] and Lin[(14)] conducted their experiments in a vacuum environment, with improved apparatus equipped with a heating element and cooling coil at each end of the experimental column to avoid any disturbance of the specimens. They concluded that conductance to heat flow at the interface of dissimilar metals does depend upon the direction of heat flow.

According to Rogers'[(13)] conclusion, "The results indicate that the effect could be associated with the mechanism of conduction at the points of metallic contact, e.g. when metals having different values of the work function are in contact a potential barrier is created which might reduce the drift of free electrons in one direction and increase it in the other." In Lin's conclusion, as evidenced by his experimental results, if the difference in the thermal conductivities of matching materials is small, then the directional phenomenon of heat flow is also small. He also suspected that other properties such as linear expansion, the modulus of elasticity, Poisson's ratio and the magnitude of the temperature gradients probably have an effect on the contact area and therefore on interface conductance.

Moon and Keeler(15) considered that when two metal surfaces were brought together, a direct metal-to-metal contact did not exist across the entire interface because of oxide film. For example, aluminum, one of the heat transfer metals used in Rogers' work, was rapidly coated with an oxide film greater than 20 Å thick when exposure to air. By applying the theory of heat conduction in the solid state, they were able to prove that an electronic potential barrier at the junction could cause a directional heat transfer effect.

Clausing(16) explained that the directional effect could be qualitatively predicted from the influence of thermal strain. Two cylinders of dissimilar metals in contact are shown in Figure 3. For the purpose of analysis, he divided the apparent contact area into two regions; the contact region and the noncontact region. The noncontact region was defined as the portion of the interface which contained few or no microscopic contact areas. The contact region, referred to as the macroscopic contact area, was the portion of the

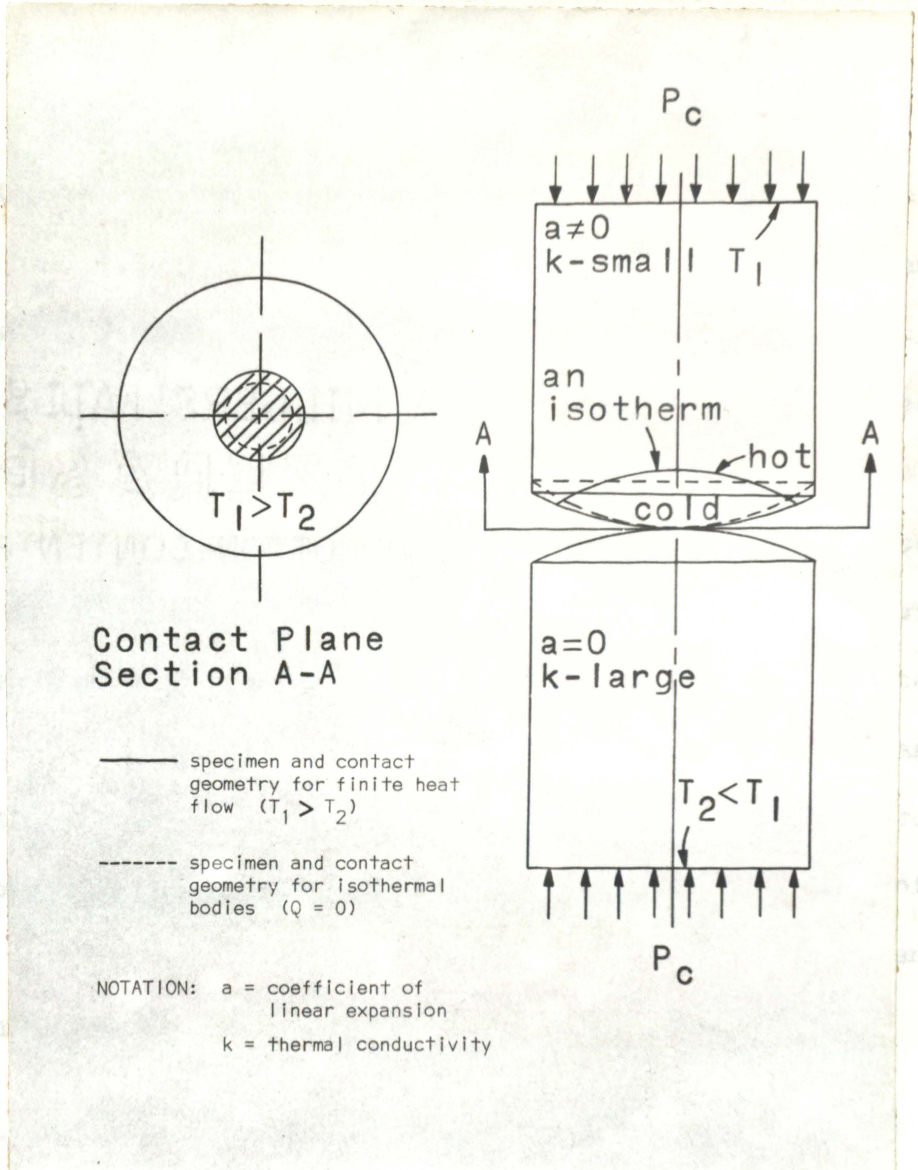

Figure 3. Effect of Thermal Strain Resulting From a Macroscopic Constriction

interface where the density of the microcontacts was high. The coefficient of linear expansion of the lower member was assumed to be zero. Then, if heat is flowing from the upper member to the lower member, the portion of the upper member near the macroscopic contact area is cold relative to the rest of the member. Thus, this region contracts, which causes the formulation of a larger macroscopic contact area than that which is predicted if only the mechanical stresses are considered. The reversal of the heat flow causes a smaller contact area than predicted from mechanical stresses alone. If the heat flow is from the upper to the lower member, the thermal strain causes a decrease in the macroscopic constriction resistance whereas a heat flow in the opposite direction causes an increase in the constriction resistance. The thermal contact resistance thus becomes a function of the direction of heat flow and the magnitude of the temperature gradients. Figure 4 is a curve taken from Reference (16) which shows the influence of the direction of heat flow on the contact resistance expressed in terms of a dimensionless resistance R*.

Since the interface conductance is so sensitive to the contact surfaces it is difficult to reproduce even under identical conditions. Smuda and Gyorog[17], by comparing the experimental results of Clausing and Chao[8], Fried[7] and Yavonovich[18], believe that coarse finished surfaces appear to permit more reliable contact heat transfer prediction and provide more reproducable test data. Very fine finished surfaces (such as optically polished surfaces) resulted in the least reproducibility and predictability.

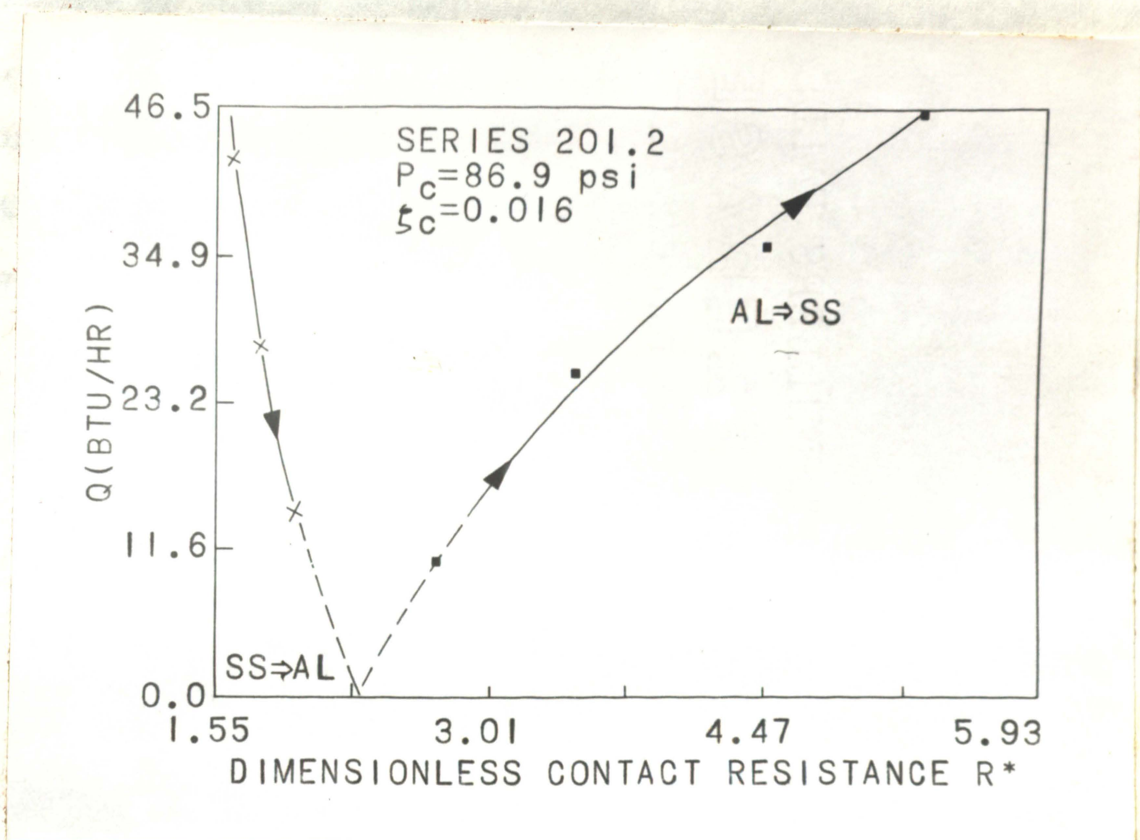

Figure 4. The Influence of the Rate of Heat Flow on the Contact Resistance : Stainless Steel - Aluminum Interface

Smuda and Gyorog[17] also found that thermal contact conductance values determined as a result of unloading the junction were approximately 25 percent higher than loading values. This phenomenon has also been noted by Clausing and Chao[8], Fried[7] and Yavonovich[18]. Smuda and Gyorog explained this is a result of changing contact surface by loading and unloading. As the surfaces are loaded, there is a tendency for microscopic protuberances to be flattened, resulting in a smoother surface. Thus, as would be expected, unloading the interface to some lower value will result in a higher value of contact conductance due to a smoother surface.

III. DESCRIPTION OF APPARATUS

The thermal conductance apparatus used in this investigation consisted essentially of two heating-cooling heads, two cylindrical test specimens, one force transducer, installed on a vertical column, under axial load with the contacting surfaces located at mid-height between the two heating-cooling heads. The axial load was supplied by a hydraulic piston press located at the bottom of the main cylindrical column. A photograph of the experimental facility is shown in Figure 5, and a schematic diagram of the test apparatus is shown in Figure 6.

A. Test Specimens

The test specimens which were used to provide the interface for testing were 6061-T6 aluminum, 1 inch in diameter and 4 inches long located between the two heating-cooling heads.

Since the surface condition is a major factor affecting thermal contact resistance, extreme care was taken in finishing the contact surface. Both the contact surface and the reverse surface of each aluminum specimen were finished with a lathe.

The surface roughnesses of the contact surfaces ranged from approximately 25 micro-inches to 35 micro-inches, rms. Roughness measurements were made using a Bendix Micrometrical Profilometer and a Profilometer Amplimeter. The roughness value selected was an average of several passes made in two directions perpendicualr to each other. Therefore, the roughness value was a running average

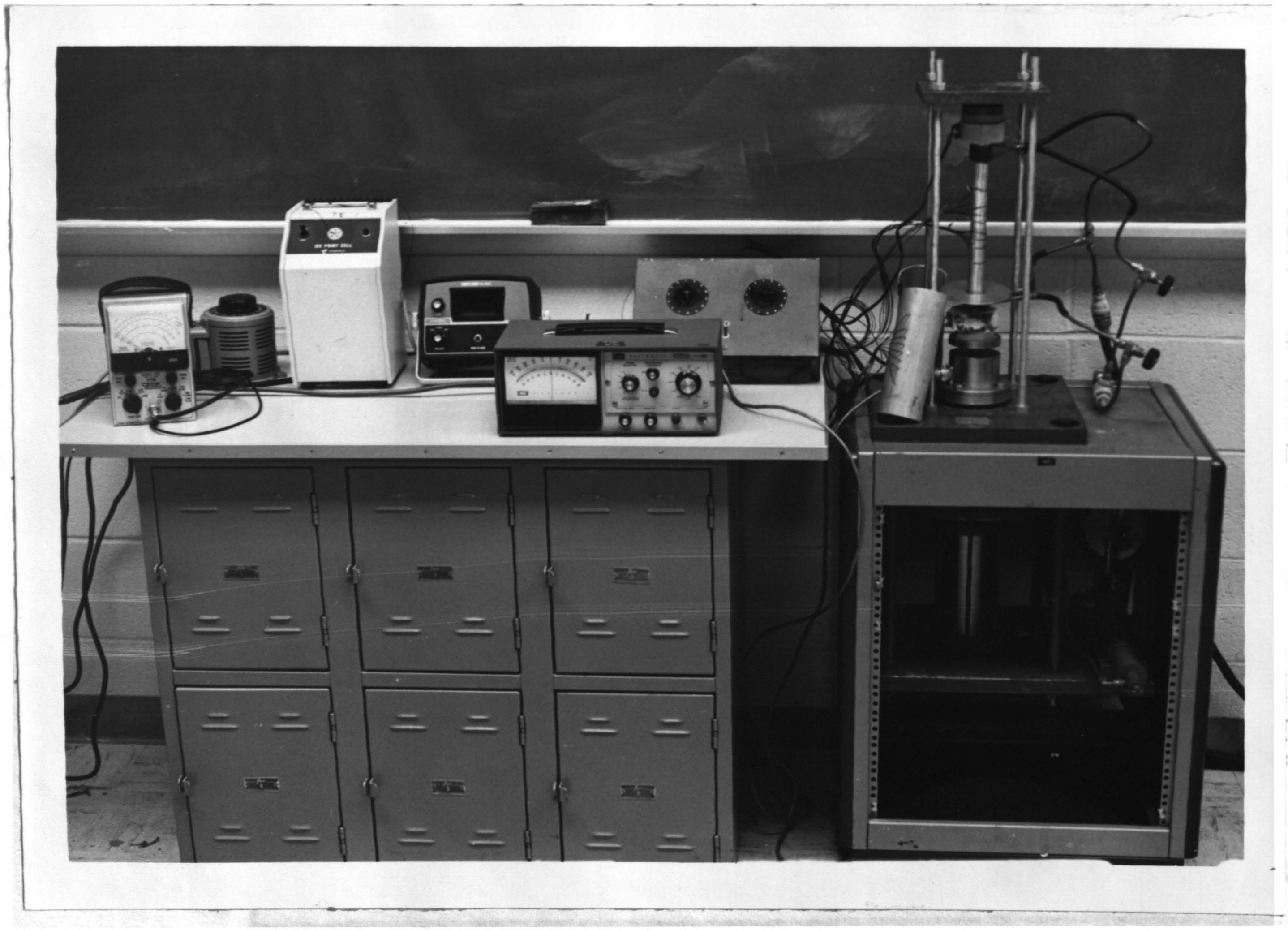

Figure 5. Experimental Apparatus

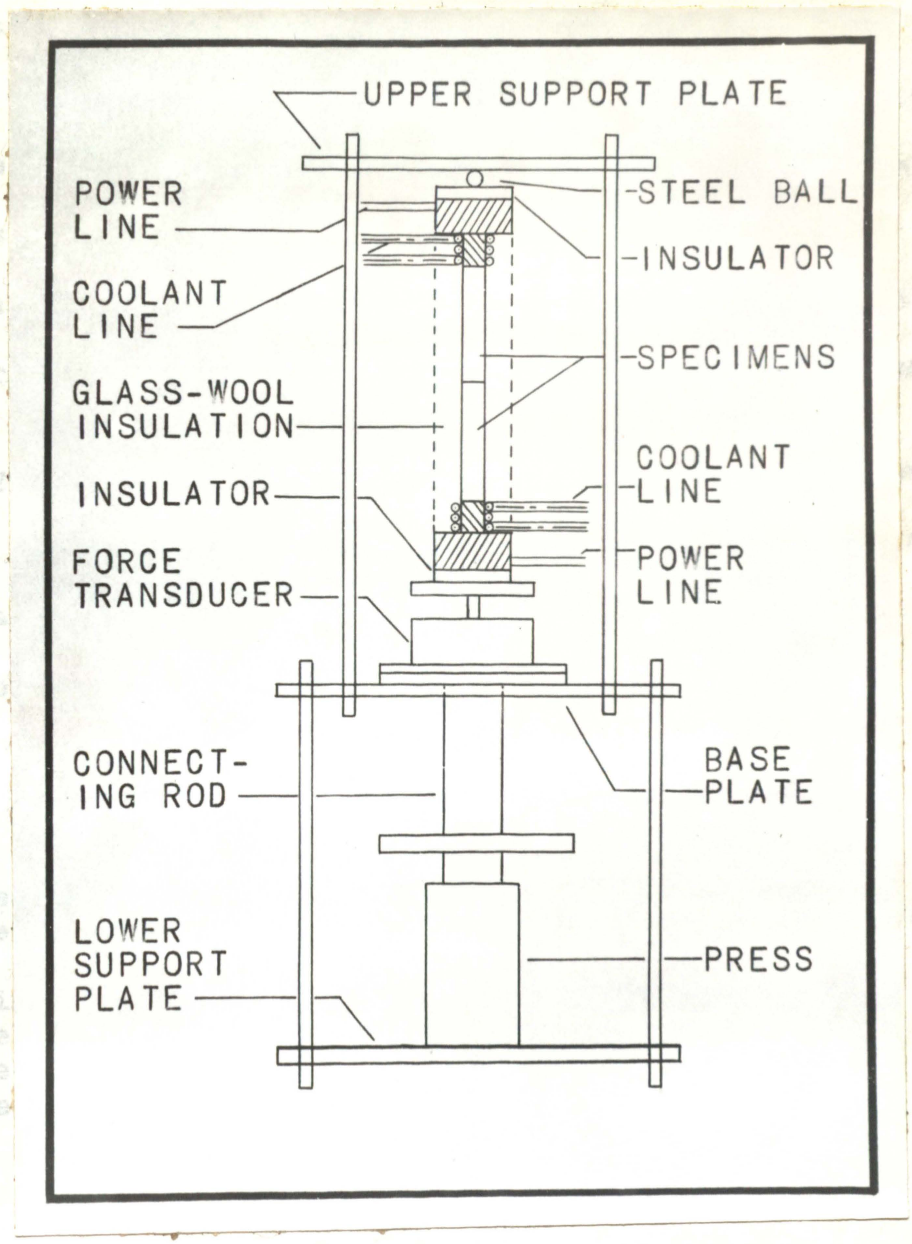

Figure 6. Contact Conductance Fixture

of the small surface perturbations.

Four thermocouple holes, 0.0635 inches (No. 52 Drill) in diameter and 0.5 inches deep, were drilled in each specimen. The spacing of thermocouple holes is indicated in Figure 7. Special care was taken to drill the thermocouple holes perpendicularly to the axis of the specimen. Two thermocouples were installed in each hole; one in the center of the hole, and the other on the surface. All thermocouple were kept firmly in position with EPOXE cement.

Eight interstitial materials were selected for this investigation. These included four stainless steel wire screens, aluminum foil, paper, and two dielectric greases. Table 1 shows the specification of these materials.

Table 1

Interstitial materials	mesh/linear in.	wire dia.	% open area
stainless steel wire screen	100/in.	0.004"	36.0 %
	40/in.	0.0065"	54.8 %
	30/in.	0.0065"	64.8 %
	10/in.	0.025"	56.3 %
aluminum foil	0.001" (thickness)		
paper	0.005" (thickness), 20 pound bond, 50% rag		
dielectric grease (1)			
dielectric grease (2)	G.E. INSULGREASE G-640 (silicone compound)		

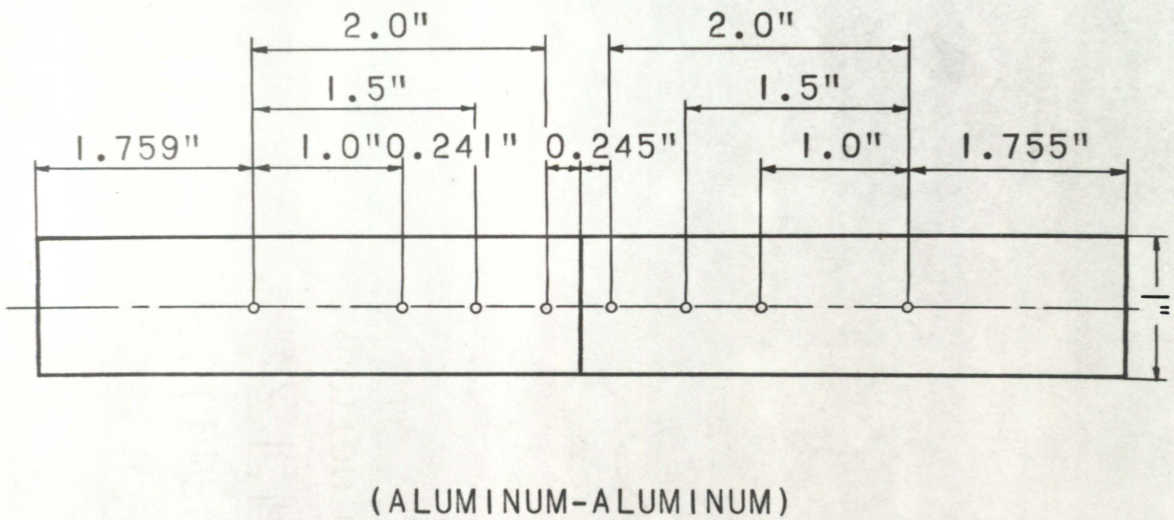

Figure 7. Specimen Configuration (Al-Al)

B. Heating-Cooling System

Two heating-cooling heads were located at both ends of the test specimens. Heat was supplied through a variable autotransformer. Water at approximately 60 ^{o}F was supplied as the coolant fluid.

The heating-cooling head consisted of two sections, i.e., heater and heat sink. The heater was an aluminum cylinder 2.25 inches in diameter, and 1.25 inches high. Around this cylinder was wrapped a single layer of 16 turns of B and S Gauge No. 22 asbestos covered Chromel "A" resistance wire. The resistance of the wire was measured at approximately 13 ohms. After wrapping the resistance wire, the outside surface of the resistance wire was coated with a layer of electrotemp cement (made by Sauereisen Cements Company) for protecting and for securing in place.

The heat sink was a smaller aluminum cylinder, 1 inch in diameter and 1.25 inches high wrapped with 4 turns of 1/4-inch copper tubing as a cooling coil, and connected to the heater as a one piece.

C. Insulation

The axial insulators were made from two 0.5-inch asbestos boards, placed at both ends of the two heating-cooling heads to minimize the heat loss from axial direction.

The test pieces were wrapped with 1-inch thick glass-wool insulation. The insulation was enclosed in an aluminum can. Eight thermocouples were installed on the can and attached to the outside surface of the glass-wool insulation for measuring the radial temperature gradients. These thermocouples were similarly located in almost exactly corresponding positions of thermocouple holes on all specimens.

D. Thermocouples

The purpose of the thermocouples was to determine the axial and radial temperature gradients. Twenty four thermocouples were installed on the specimens and the insulation guard.

In view of the characteristics of the various types of thermocouples, a 28 gauge cooper-constantan was selected since it is easy to fabricate and dependable over the temperature range of this experiment with an accuracy of 1.5 ^{o}F when carefully calibrated.

The thermocouple junctions were made with DYNATECH thermocouple welder Model 116 to insure near perfect junctions.

The leads were wrapped once around the specimen to minimize heat losses through the wire. The thermocouples were held in position by applying EPOXE cement. After being fixed into position, the continuity of the thermocouple was checked again by measuring the resistance.

All thermocouples were connected to a cold junction by two selector switches which in essence provided an individual cold junction for each thermocouple. The cold junction thermocouple was placed in the DYNATECH ice point cell to provide an accurate 32 ^{o}F reference temperature. The thermocouple outputs were read from a DIGITEC Model 454 millivolt potentiometer, and converted into degrees Fahrenheit according to the conversion tables of National Bureau of Standards, Circular 561.

E. Loading System

A hydraulic piston press was assembled at the end of the main vertical column to provide an axial load to the contact surfaces.

In order to achieve axial loads on the test column, a steel ball was positioned between the upper support plate and heating element. The test column sat on a force transducer connected to the press by an aluminum connecting rod. The entire apparatus was assembled as shown in Figure 6.

A DAYTRONIC Model 152A-1000 force transducer and a DAYTRONIC Model 300 C Transducer Amplifier-Indicator were used to indicate the force on the contact surfaces. Before installation, the force transducer was calibrated to a full scale of 700 pounds. The force transducer consisted of a primary coil and two secondary coils which were symmetrically arranged to form a hollow cylinder. A small magnetic iron core was arranged to move axially within the cylinder in response to the mechanical input to the probe. Since the two secondary coils were connected in series opposition, when the primary coil was excited by a source of atternating current, and if core was in the center or "null" position, the AC voltages induced in the secondary coils would be equal and cancel each other due to opposite phase. However, if the core is displaced from the null position by axial load, one secondary voltage would increase while the other would decrease, and a net output signal voltage would be produced, which, through proper design, would be proportional to the magnitude of displacement from "null", and hence proportional to the magnitude of the axial load. The net output signal voltage was fed into the Transducer Amplifier-Indicator to indicate the output voltage. From this, the axial load could be calculated. The Transducer Amplifier-Indicator consisted of an AC voltage agitator and an ordinary amplifier to cooperate with force transducer.

F. Instrumentation

A schematic diagram of the total instrumentation, power sources and liquid flow lines is shown in Figure 8.

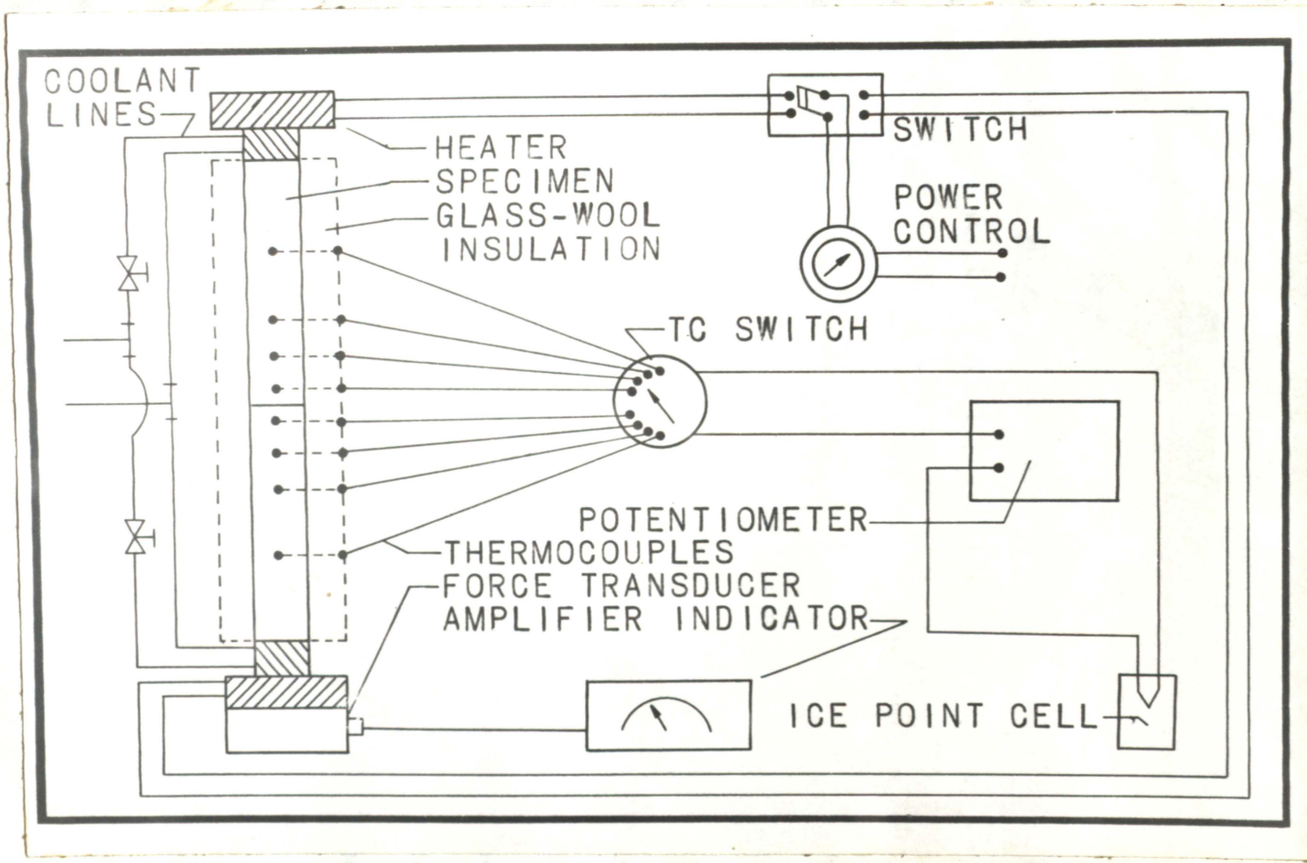

Figure 8. Schematic of Experimental Apparatus

IV. TEST PROCEDURE

After assembly of the test apparatus, the initial tests were conducted with an aluminum bare junction. The purpose of these tests was to check the performace of the apparatus and the validity of the measured data.

The specimens were placed in the test apparatus. Special care was taken to keep the specimens aligned and in good contact. After the equipment was assembled and pressurized to the lowest test pressure, the specimens was wrapped with glass-wool insulation. Power was then applied to the heater at one end of the specimen and the copper tubing at the end of the other test specimen was supplied with cooling water. The input power to the heater was controlled by a variable voltage transformer. A steady-state condition was determined by periodically monitoring the temperature of the test specimens. Generally, from three to four hours were required to attain a steady-state condition. When the test data were recorded for a given load and supplied power, the heat flow was reversed to measure the conductance in the opposite direction of heat flow.

The same experimental precedure was followed for all interstitial material tests. A one inch diameter disk of the interstitial material was placed between the contacting surfaces, the equipment was assembled, and the same test procedures were followed.

After each run of interstitial material, the contact surfaces were slightly indented. Therefore, before testing a new interstitial specimen the contact surfaces were refinished.

The experimental tests with bare junctions and with interstitial materials were conducted in the order of increasing load pressure, i.e. the lowest test pressure was run first, followed by the next lowest pressure.

V. ANALYTICAL ANALYSIS

All data obtained from the experiment were fed into an IBM 360 Computer programmed for a least squares method to fit a temperature distribution equation. This was extrapolated to the interface to obtain the temperatures at each side of the interface in contact. The temperature drop across the interface was thus obtained.

In order to simplify to one-dimensional heat flow and to derive the temperature distribution equation, two assumptions were made:

(1) Uniform thermal conductivities K, K' existed throughout the specimens and the glass-wool insulation respectively.

(2) Radial temperature gradients were so small that the temperature at any cross section of the rod was uniform, i.e., $T = T(X)$ only.[19]

The limitations of this simplification, which reduce the problem to one-dimensional heat flow, have been investigated analytically by Harper and Brown[20]. The results of this study show that, even in a relatively thick cross sectional area, the error in the one-dimensional solution is less than one per cent.

Under steady-state conditions, the rate of heat flow into the element is equal to the rate of the heat flow out of the element, as shown in Figure 9, or

$$-KA\frac{dT}{dX} = \left(-KA\frac{dT}{dX} + \frac{d}{dX}\left(-KA\frac{dT}{dX}\right)dX \right) + h(T-T_o)dX, \tag{1}$$

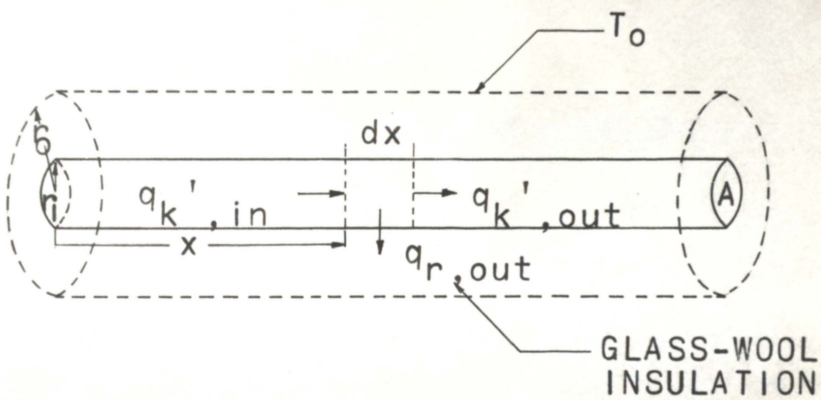

Figure 9. Sketch and Nomenclature of Test Specimen

where K is thermal conductivity of specimen, T_o is the temperature of outside surface of glass-wool insulation and

$$h = 2\pi K'/\ln(r_o/r_i) .$$

Hence

$$h(T-T_o)dX = \frac{2\pi K'}{\ln(r_o/r_i)} (T-T_o)dX = q_r, \quad \text{where} \qquad (2)$$

K' is the thermal conductivity of glass-wool insulation, q_r is the heat loss from radial direction.

Equation (1) can be simplified to

$$\frac{d^2T}{dX^2} = m^2(T-T_o) , \qquad (3)$$

where $$m^2 = h/KA = \frac{2\pi K'}{\ln(r_o/r_i)KA} .$$

From experimental data show that the temperature range of T_o is within 5 ^oF, compare to the temperature range of T is so small that T_o can be considered independent of X. Thus equation (3) is a standard form of an ordinary second-order linear differential equation whose general solution is

$$T - T_o = C_1 EXP(mX) + C_2 EXP(-mX), \qquad (4)$$

where C_1 and C_2 are constants of integration whose values must be determined from the boundary conditions, i.e., from experimental data to fit this temperature distribution by the least squares method.

The axial heat transfer rate is found from

$$q_k' = KA\Delta T/L, \tag{5}$$

where ΔT is the temperature difference between two holes a distance L apart, A is the cross sectional area of the test specimens, and K is the thermal conductivity of the test specimen.

The radial heat transfer rate q_r is found from equation (2).

After q_k' and q_r are obtained, the interface conductance is determined by the equation

$$H = q_k/(A\Delta T_{interface}), \tag{6}$$

where $\Delta T_{interface}$ is the temperature difference of contact surfaces, and q_k is the average heat transfer rate across the interface obtained from the average value of heat flow rate at two contact surfaces.

VI. RESULTS AND DISCUSSION

The results of the tests made to determine the conductance of various interface joints are shown in figure 10 through 16. These plots show the direction of heat flow, the interface conductance at different contact pressure levels and the mean interface temperatures.

Aluminum Bare Junction :

The results are plotted in Figure 10 and 11. The two specimens were both 6061-T6 aluminum alloy. The thermal conductivity of this aluminum is about 99 Btu/hr sqft ^{o}F[14].

The first preliminary test was made to determine the performance of the test apparatus. The results are plotted in Figure 10. Comparing this with Reference (6), the results are about 20 percent lower. Since contact conductance is very sensitive to test conditions, in this experiment the test conditions could not be maintained exactly the same as those in Reference (6). In order to confirm the validity of this test apparatus, the same surface configuration was run once again, and the results of second run are plotted in Figure 11. The second set of results agree within 5 percent of the first test. The values of the interface conductances ranged from about 430 Btu/hr sqft ^{o}F to 800 Btu/he sqft ^{o}F for contact pressures of 100 psi to 600 psi, and increased about 50 Btu/hr sqft ^{o}F as the mean interface temperature increased from 100 ^{o}F to 200 ^{o}F at 100 psi, and about 130 Btu/hr sqft ^{o}F at 600 psi.

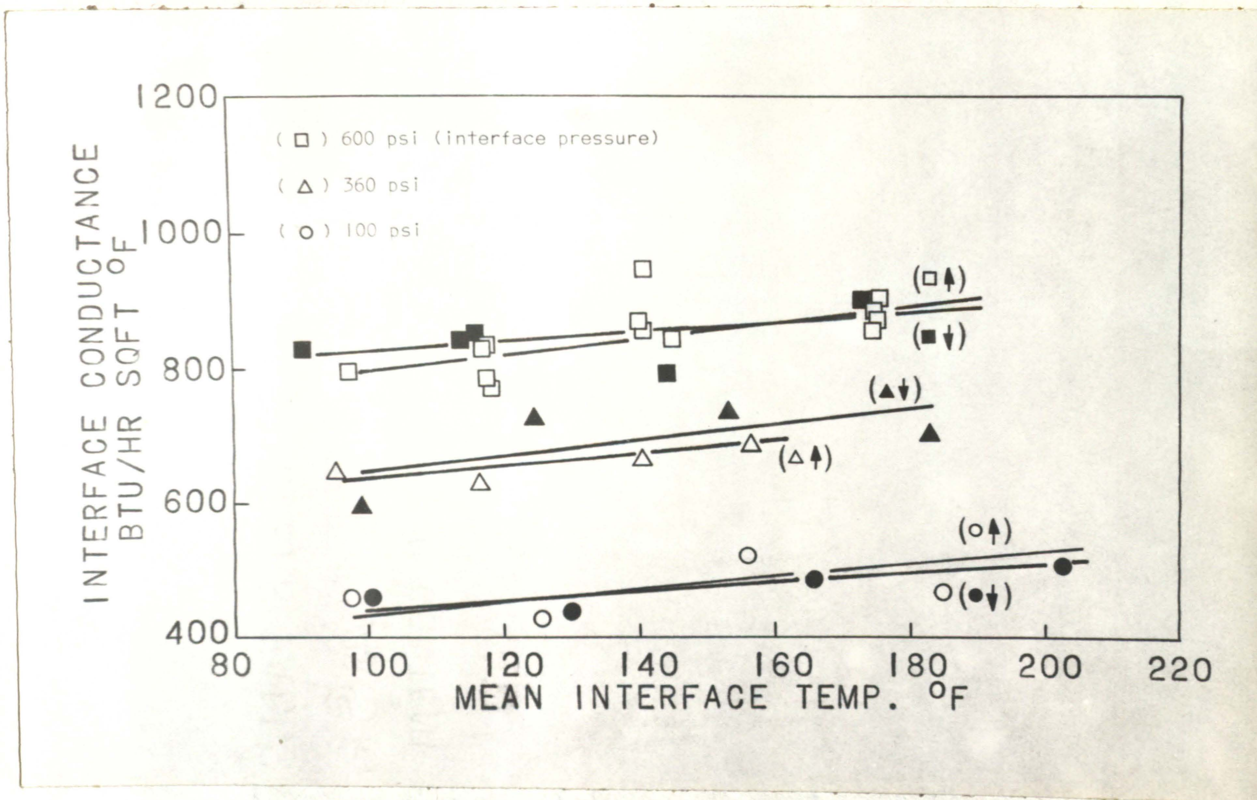

Figure 10. Interface Conductance of Aluminum Bare Junctions (1)

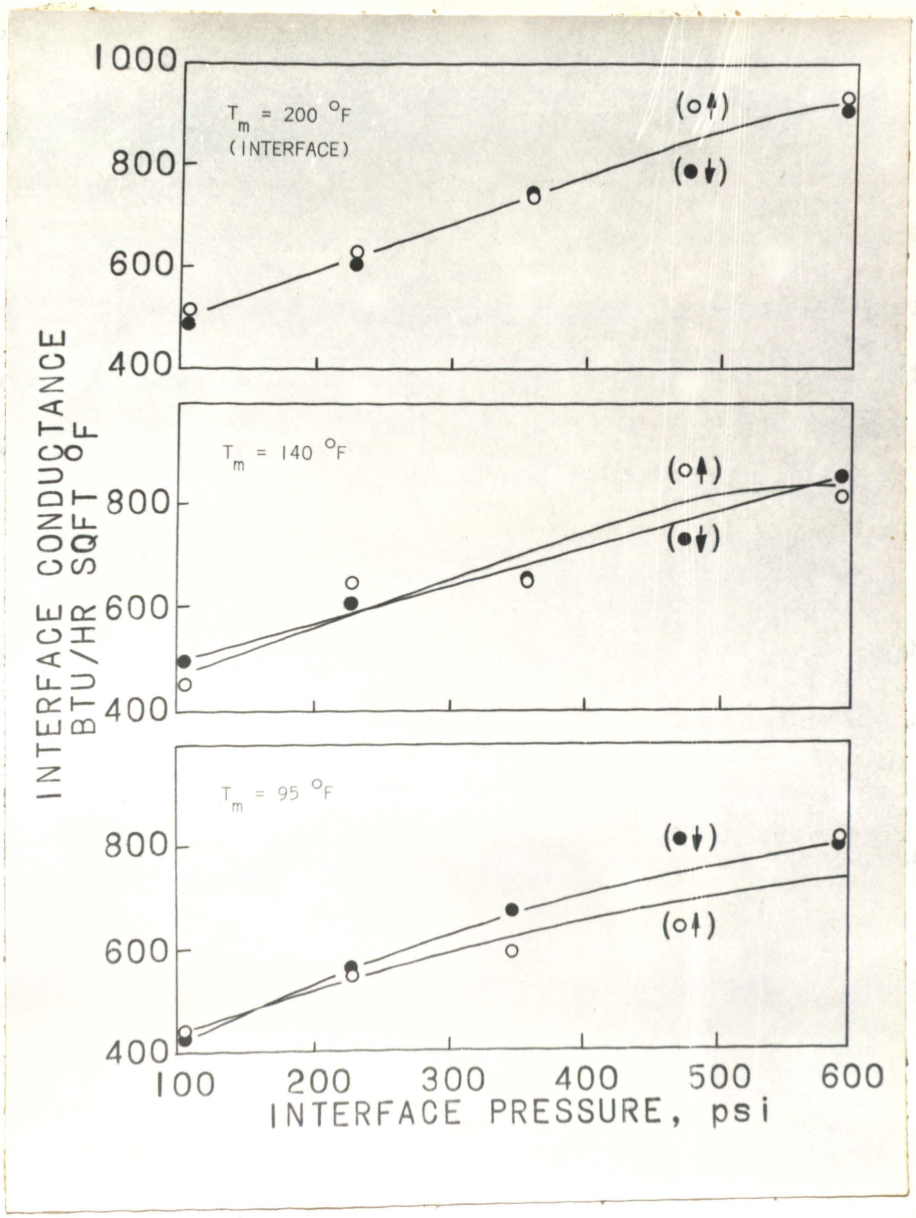

Figure 11. Interface Conductance of Aluminum Bare Junctions (2)

For the purpose of better comparison with the results of interstitial materials, the data of the second run are plotted with interface conductances as the ordinate and contact pressures as the abscissa.

Effect of Interstitial Materials :

The interstitial materials used in this experiment were stainless steel wire screen, paper, aluminum foil, and dielectric grease. The specimens used to provide the interfaces throughout this experiment were 6061-T6 aluminum.

(1) Stainless Steel Wire Screen :

The four different wire screen materials listed in Table 1 were tested. The test results are shown in Figure 12. When sandwiched with wire screen, the contact points at the interface occur only where the wire screen weave overlaps. As the mesh size was increased, the contact points also increased. As shown by 100 and 10 mesh stainless steel wire screens, the interface conductance of the 100 mesh screen is greater than the 10 mesh screen. This is due to the larger number of contact.

As may be seen in Figure 12, the 10 mesh wire screen is less dependent on pressure compared with the other three wire screens. As the wire screen is subjected to the interfaces, the pressure is concentrated at limited contact points. The smaller number of contact points result in greater pressure concentration. In the case of the 10 mesh size, the pressure at the contact points is so large that the wires embed into the aluminum surfaces and plastic deformation occurs. Increasing the contact pressure no longer increases the contact area. Hence the pressure range of this test was increased from 100 psi to 500 psi only to increase the interface conductance of 10 mesh stainless steel wire screen by about 23 Btu/hr sqft ^{o}F.

In general, wire screens have the advantage of limiting the contact area with the plane metal surface. Therefore they offer a good thermal resistance to heat transfer. In addition, the wire screens can stand high contact pressure and produce strong structures. This provides a wide application in engineering design.

The mean interface temperatures also had an effect on interface conductances of wire screens. As mean interface temperatures were increased from 100 ^{o}F to 180 ^{o}F, the interface conductance increased about 15 Btu/hr sqft ^{o}F for 100 mesh wire screen. This increment was less noticeable as the mesh number was decreased.

The convection heat transfer caused by interstitial gas was not serious and it was difficult to determine the percentage of heat transfer contributed by convection. This is shown by the results presented in Figure 12. When the direction of heat flow was reversed, the interface conductance varied only about 9.2 % for the worst case, and the interface conductances of the upward direction of heat flow were not always greater than those of the downward direction. They should always be greater in the case where convection heat transfer has noticeable effect.

The results were scattered for 40 mesh stainless steel wire

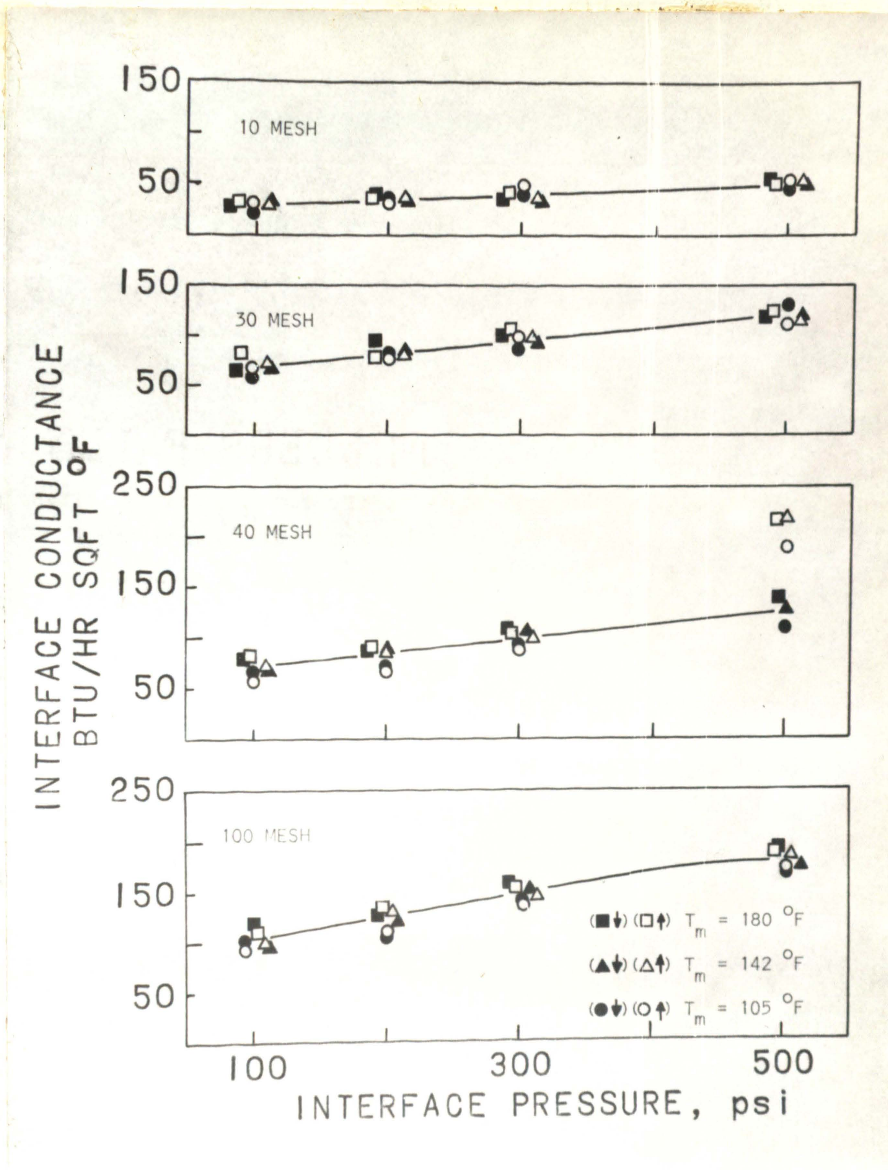

Figure 12. Interface Conductance of Aluminum Junction Sandwiched with Stainless Steel Wire Screen

screen at 500 psi as shown in Figure 12. It is believed that at this pressure level, the wire screen was deformed and provided larger contact area, and this resulted in a larger value of interface conductance. This did not happen again for other tests of wire screens.

(2) Paper Sheet and Aluminum Foil :

Figure 13, when compared with Figure 11, shows that the effect of paper sheet (0.005 inches thick) was to lower the interface conductance, for aluminum interfaces at pressures up to 300 psi, by about 70 %. Paper has the same effect as wire screen, only it can not stand the high pressure.

The aluminum foil (0.001 inch thick), on the other hand, was to increase the interface conductance about three times as much as that of aluminum bare interfaces, as shown in Figure 14. Both the paper sheet and aluminum foil could increase contact area when they were inserted into the interface. However, because of their thermal properties one decreased the interface conductance and the other increased it.

(3) Dielectric Grease :

Two kinds of greases were tested. These were grease-like silicone compounds with high thermal conductivities. When used as interstitial materials, they took the place of interstitial gas and filled the voids. They became excellent channels for heat flowing. As shown in Figures 15 and 16, the values of interface conductances increased by a factor of 10 compared with aluminum bare interfaces.

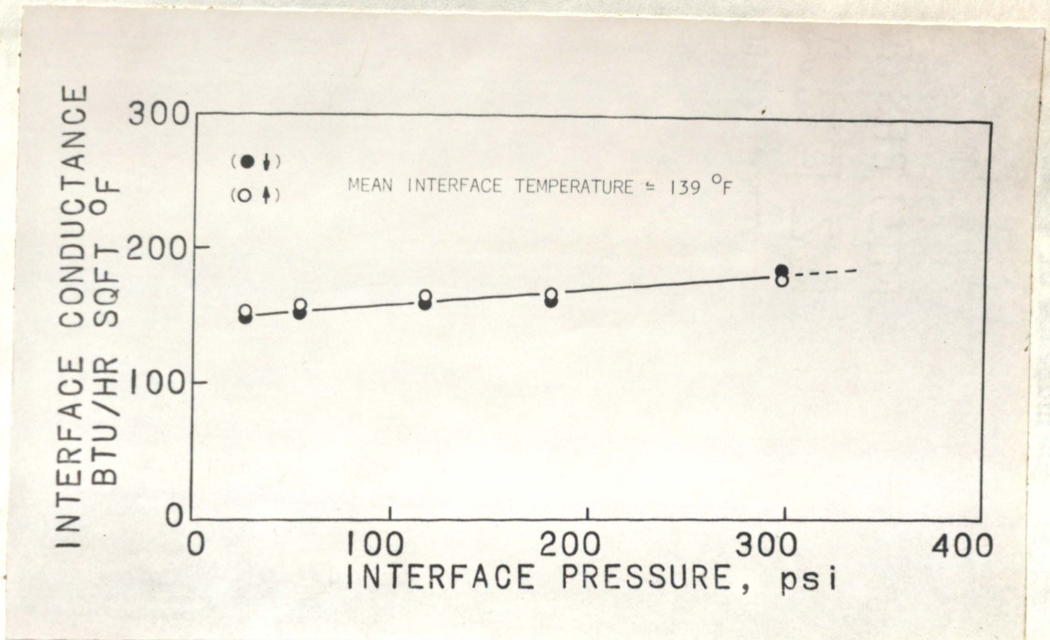

Figure 13. Interface Conductance of Aluminum Junction Sandwiched with Paper

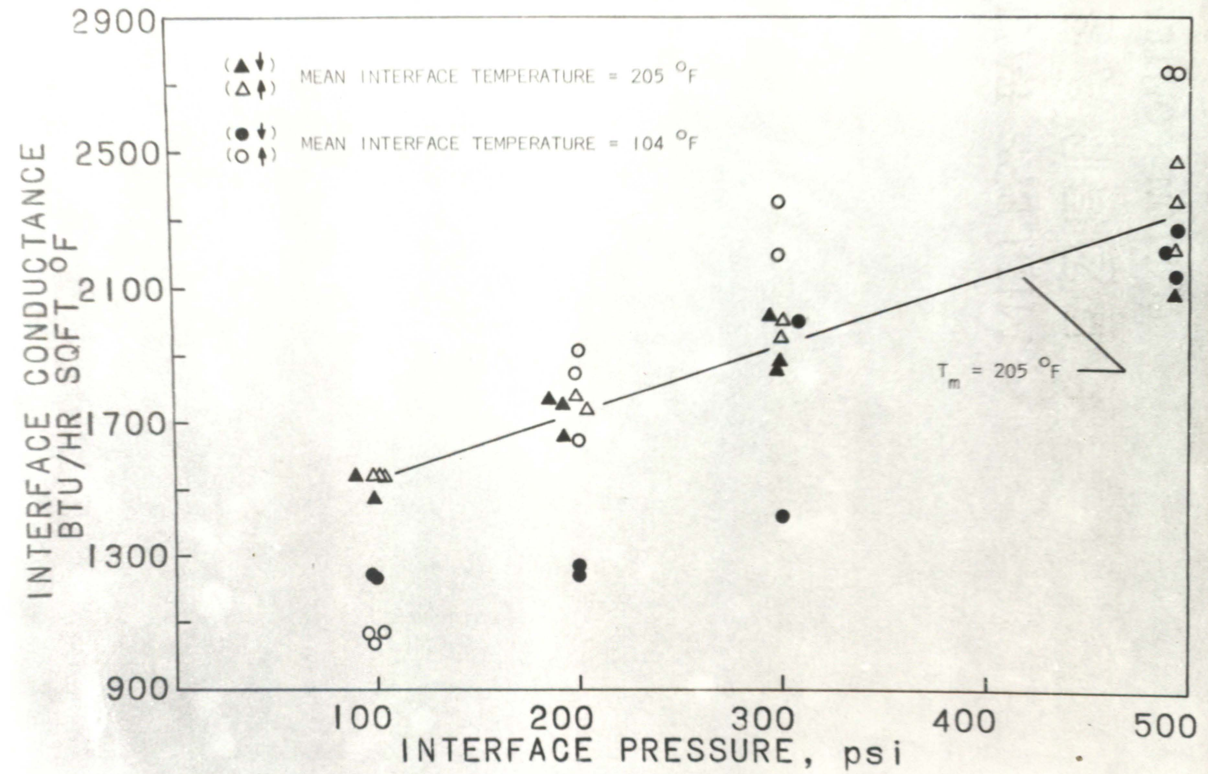

Figure 14. Interface Conductance of Aluminum Junction
Sandwiched with Aluminum Foil

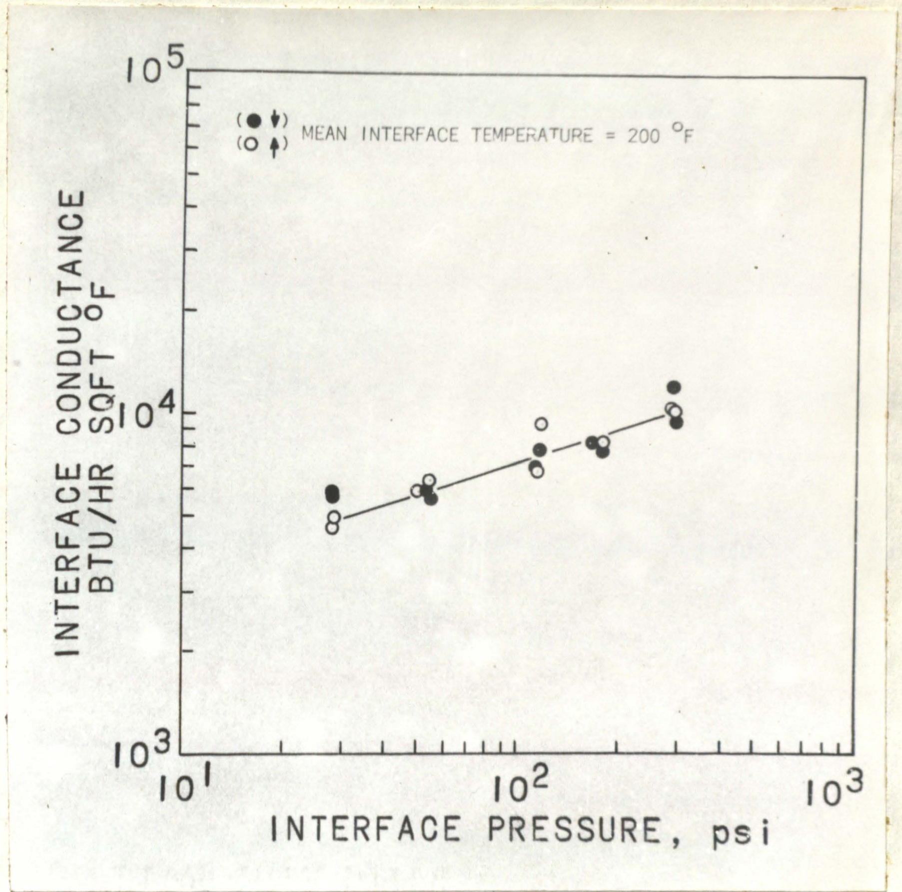

Figure 15. Interface Conductance of Aluminum Junction Sandwiched with Grease (1)

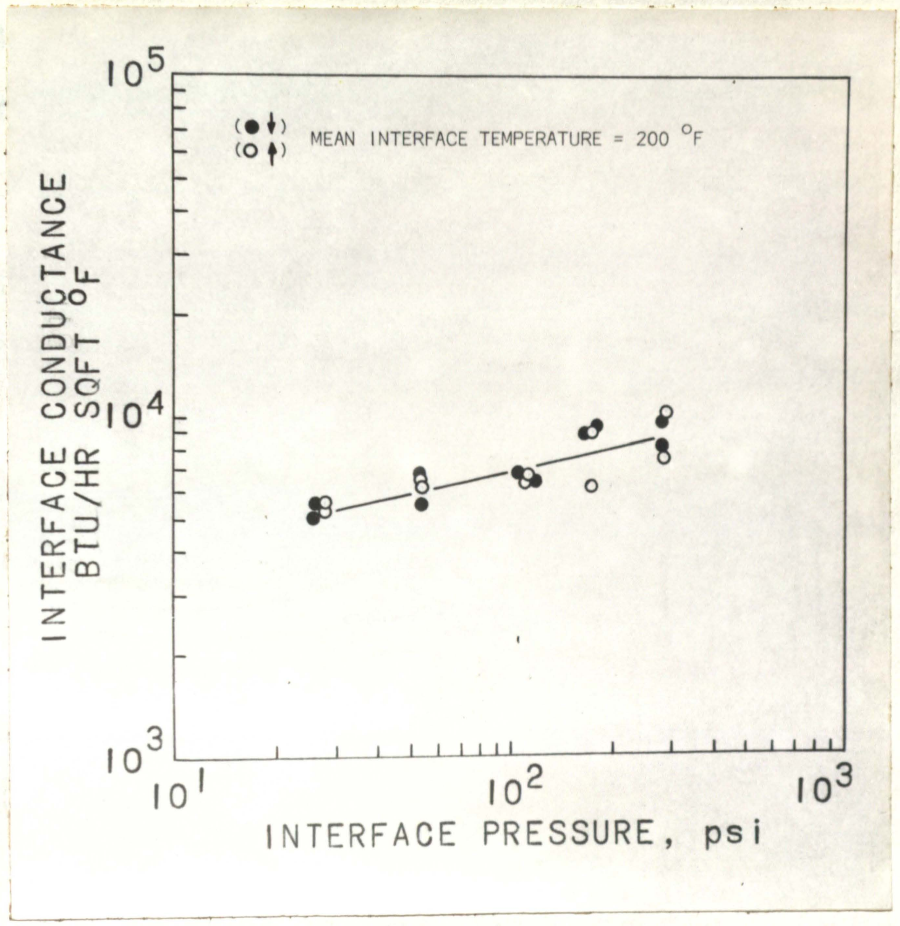

Figure 16. Interface Conductance of Aluminum Junction Sandwiched with Grease (2)

VII. CONCLUSIONS

The following conclusions were drawn upon examination of the experimental results of interface conductance measurements :

1. Interstitial materials may either increase or decrease the interface conductance over that of the bare interface depending upon the thermal properties of interstitial materials.

2. When sandwiched with wire screen, the contact pressure is concentrated over a limited area and plastic deformation is likely to occur. When it does, the interface conductance is less dependent upon contact pressure, since increasing the contact pressure no longer increases the contact area.

3. When sandwiched with wire screen, the interface conductance is decreased as the mesh number of wire screen is decreased. This is a direct result of decreasing the contact area.

4. The heat transfer contributed by convection in the interstitial gas is very small or negligible.

5. The effect of a 0.005-inch-thick paper sheet sandwiched between the aluminum surfaces was to decrease the interface conductance for aluminum interfaces, for pressures up to 300 psi, to about 70 percent of the bare junction value.

6. The effect of a 0.001-inch-thick aluminum foil was to increase the interface conductance about three times that of an aluminum bare junction.

7. Dielectric grease with high thermal conductivity fills the voids between the contact surfaces providing excellent heat flowing channels, and thus increases the interface conductance by a factor of 10 compared with aluminum bare junctions.

VIII. RECOMMENDATIONS

Modification of some of the apparatus is recommended to improve the results. Increasing the power of the heater, and using cooler circulating water to get larger temperature gradients at the interface, would produce more accurate results. Care should be taken to minimize oxidization of the test specimens to obviate the problem of surface contamination. Further recommendation of getting more data, i.e. specimen materials, surface conditions and finishes, and test conditions, are suggested to gain more knowledge of the behavior of heat transfer across the interface.

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X. VITA

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